Material Selection for Far Infrared Telescope Mirrors

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ABSTRACT

Large visible telescopes present challenging requirements for manufactured surface figure and stability. By comparison, far infrared (IR) telescopes relax many of these requirements by ~100x. These relaxed requirements may translate into reduced cost, schedule, mass, and system complexity. This paper explores how different mirror substrate materials might take advantage of these requirements while operating in a cryogenic environment. Primary mirror materials are evaluated for an Origins Space Telescope (OST) concept, using a 9.1 m segmented aperture in a 30 μm diffraction limited system.

Keywords: Infrared, Mirror, Substrate, Segmented, Materials, Cryogenic

1. BACKGROUND

IR space telescopes have been demonstrated up to 3.5 meters in aperture, as in the case of the Herschel Space Observatory. Long wavelength IR observations are needed to detect gasses which are key building blocks for life. Detection of atmospheric gasses surrounding exoplanets requires high-contrast IR observations. The high-contrast requirement drives the need for larger apertures. Telescopes such as Spitzer have also operated at temperatures as low as 4 kelvin. A cold telescope operating temperature is necessary to create a quiet thermal background for long-wave IR observations. Primary mirrors for IR telescopes have successfully been made from Corning ultra low expansion glass (ULE®), silicon carbide (SiC), aluminum, beryllium, and fused silica (SiO_2), among others. Table 1 describes a broad range of heritage experience, spanning various materials, different optical requirements, and different temperatures.

Table 1 Recent History of Comparable Space Telescopes

Mission	Launch Year	Aperture Diameter	Aperture Area	Mass	Areal Density	Substrate Material	Shape Control	System Design Diffraction Limited Wavelength	Thermal Control Approach	Temperature
		(m)	*(m^2)*	*(kg)*	*(kg/m^2)*					*(K)*
Hubble	1991	2.4	4.03	1000	180	ULE	Passive	0.5	Active	293
WMAP	2001	1.5	3.52	17	10	Composite	Passive	3200	Passive, Open	90
Spitzer	2003	0.85	0.54	15.3	28	Be	Passive	6.5	Cryogen	4
GeoEye	2008	1.1	0.85	34.7	41	ULE	Passive	0.5	Active	293
Herschel	2009	3.5	9.24	300	32	SiC	Passive	80	Passive, Open	80
Kepler	2009	1.4	1.54	87	57	ULE	Passive	1.7	Active	178
WISE	2009	0.4	0.11	9.3	88	Al	Passive	~12	Cryogen	10
GAIA	2013	1.5	0.86	38	22	SiC	Passive	1	Passive, Open	130
OPTIIZ	2015	1.5	0.98	19.9	15	Nanolaminate/SiC	Active	1	Active	293
IceSat-2	2016	0.8	0.47	12.8	27	Be	Passive	1.5	Active	
JWST	2020	6.5	32.06	801.5	25	Be	Active	2	Passive, Open	40

The James Webb Space Telescope (JWST) serves as an ideal baseline to reference in the development of OST. JWST shares key characteristics and requirements with OST; both use a segmented primary mirror that operates at IR wavelengths and cryogenic temperatures. A rigorous study, Advanced Mirror Segment Demonstration[1] (AMSD), was performed to select a mirror substrate material for JWST. This paper emphasizes the relevance of some lessons learned during AMSD and refers to the JWST segmented beryllium mirror solution as a baseline.

2. OST REQUIREMENTS

2.l Wavefront Error Requirements

The wavefront error (WFE) budget for OST defines optical performance of the telescope system at the highest level. The total allowable WFE is a function of instrument operating wavelength and contrast performance requirements. The total allowable WFE is flowed down to define requirements for cryogenic surface figure quality, dynamic and thermal stability effects, jitter, and other effects, listed in Figure 1. A more detailed WFE budget might flow down requirements further to consider more specific errors. For example, a WFE budget might include the optical surface quality of the tested mirrors in gravity, the surface deformations at cryogenic temperature, the surface deformations from gravity, the quality of alignment of optical components at temperature, and limitations of corrective actuator capabilities. If one error source is reduced, the allocation for other error sources in the budget can be increased.

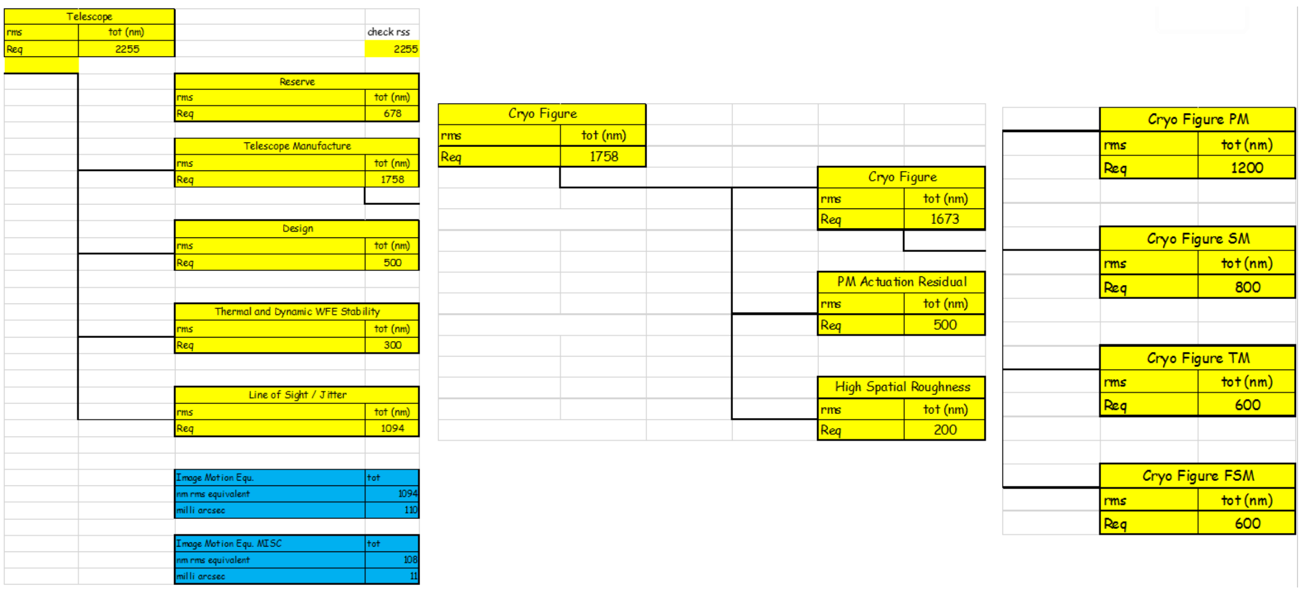

Figure 1 Notional OST Wavefront Error Budget for 30 μm Diffraction Limited Performance

Generally, some cost is associated with reducing the magnitude or uncertainty associated with each WFE effect. One example is improving the optical surface quality through the cost of additional surface metrology and figuring. Another example is that the quality of alignment at temperature could be improved by using analytical prediction of system deformation at temperature and through measuring alignment at the telescope operating temperature. The analysis and measurement each incur additional cost. Another example is the improvement of actuator resolution with the cost of stacking coarse and fine actuator technologies together. The case of choosing a mirror substrate material is no different; beryllium provides better cryogenic WFE performance at a higher cost than a glass alternative (among many other mirror performance considerations that contribute to wavefront error). The cognizant systems engineer should consider if the WFE improvement associated with beryllium allows for greater WFE allocations elsewhere in the system, resulting in less expensive technologies and reducing the overall system cost. The same questions should be asked with respect to budgets for mass, volume, and power consumption. Because there is cost associated with reducing WFE effects and the

OST WFE budget allows more error than past flagship missions like Hubble or JWST, there is opportunity for lower optical system costs for OST, so long as 4 Kelvin operating considerations do not dominate cost.

While there is cost associated with reducing WFE effects, and considering reducing one effect allows greater budget allocations for other effects, there is not always a clear path to minimizing cost and WFE effects simultaneously. This is because there is not always a clear relationship between reducing a WFE effect and cost. The relationship between cost and WFE is often obscured by the many unrelated factors that drive the cost of a telescope. Telescope architecture, manufacturing design and approach, and test methodology can all influence cost, and are not necessarily made with WFE effects in mind. For most every telescope system, the system WFE never matches the total WFE allocated in the budget. A WFE budget, as in Figure 1, tracks error sources and the uncertainty associated with each error. Usually, in the scheme of a WFE budget, the uncertainties in error effects often consume more of the budget than the effects themselves. For many telescopes, the operating WFE outperforms the predicted WFE because uncertainties often dominate the prediction-based WFE budget. For the same reason, a WFE error budget accounting for hundreds of individual error sources can fail to conservatively predict operating telescope WFE performance solely because of a single error source. In these cases, the underperformance is due to a single error source that did not carry enough uncertainty for the analysis or test that predicted the error magnitude. These factors cloud the relationship between cost and the reduction of WFE effects.

2.2 Cryogenic Survivability Requirements

ULE® and beryllium mirror assemblies have been shown to survive at temperatures as low as 30 Kelvin during AMSD.[1] These results indicate a likelihood of survivability at 4 Kelvin. Beryllium also has flight heritage down to 4 Kelvin on the Spitzer telescope. Under cryogenic thermal loads, survivability is driven by thermo-elastic stresses and deteriorated by material embrittlement. Thermo-elastic stresses are generated by the mismatch in *strain at temperature* between connected parts, not necessarily by the magnitude of the strain. In the case of a segmented IR telescope, stresses could be generated by differences in strain magnitude between any two components, such as:

- The mirror substrate and the mirror backplane
- The mirror substrate and mounting adhesives
- The mirror backplane and metallic fittings

As materials are cooled from room temperature to absolute zero, most of the strain change is observed on the range from 293 kelvin down to ~100 kelvin. Figure 2 illustrates strain with respect to temperature for commonly used materials in space telescope structures. Below ~100 kelvin, the slope of the strain with respect to temperature becomes flat for some materials. Below ~40 kelvin, the slope is nearly flat for most every material. This means at low temperatures, materials have lower coefficients of thermal expansion, and changes in temperature do not introduce much strain. For example, the strain mismatch between beryllium[4] and Stycast 2850FT(TM)[4] , an adhesive, at 40 kelvin is 97% of the mismatch at 4 kelvin. The strain mismatch between SiC[6] and beryllium[4] at 40 kelvin is indistinguishable from the mismatch at 4 kelvin.

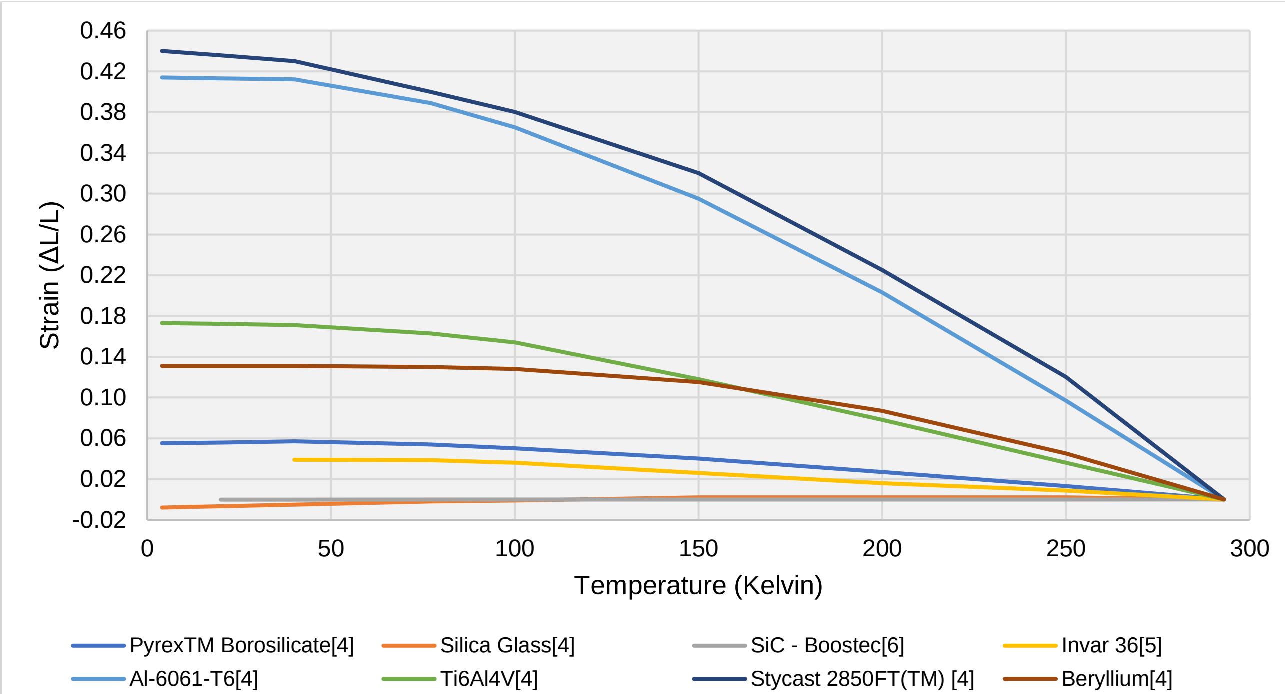

Figure 2 Material Strain with Respect to Temperature

2.3 Cryogenic Performance Requirements

Cryogenic WFE is associated with differential strain across different parts of the optical telescope assembly. There are several strategies for mitigating differential strain effects

- Using only one material
- Using materials with similar strain states at operating temperature
- Athermal design, in which parts are designed and assembled in a way such that uniform, strain-free growth is allowed
- Kinematic flexures, which allow differential strain without deforming parts

Each strategy entails challenges. The first strategy, creating an entire telescope from one material, is ideal for reducing differential strain and ensuring little-to-no deformation at temperature; however the requirements of each part in the OTA may not be satisfied. In the case of aluminum, the resulting telescope may exceed the mass or volume requirements of existing launch vehicle options. In the case of SiC, glass, or glass ceramics, the resulting telescope may be too brittle to survive launch loads, and manufacture might prove time consuming. In the case of beryllium, the telescope may be too expensive and time consuming to manufacture. All strategies listed in the bullet points above can be used together to satisfy the different requirements of various OTA components, taking advantages of various material properties where they are needed and encouraging similar strain behavior between joined parts. Engineering solutions typically apply the remaining three strategies together to address thermal telescope performance in heritage missions. Because mirror backplanes, substrates, flexures, and instrument housings have different requirements, multiple materials are typically used with these strategies to create a solution with acceptable overall cost, schedule, and risk.

AMSD evaluated two matured mirror substrate materials rigorously, ULE® and beryllium. AMSD supported the choice of beryllium for the primary mirror substrates, in spite of schedule disadvantages, because of its high performance in a cryogenic environment. AMSD demonstration mirror assemblies were built using ULE® and beryllium, and tested in cryogenic conditions. Both mirrors survived cryogenic temperatures.

After correcting for alignment aberrations, the change in surface figure between ambient and 30 kelvin was measured to be 77 nm rms for the beryllium mirror and 188 nm rms for the ULE® mirror. [1] This difference was a key differentiator in the context of the JWST < 117 nm rms WFE requirement. [1] In the context of the OST 2000+ nm WFE budget, the difference in performance is manageable. Furthermore, there is an opportunity to absorb the entire cryogenic WFE without correction. Segment costs are greatly reduced by eliminating the need for cryogenic metrology and final surface figuring steps to correct cryogenic error. The notional OST WFE budget will accommodate the cryogenic errors associated with glass mirror substrates.

While the OST WFE budget can absorb the cryogenic surface figure errors associated with a glass (ULE®) solution, it is not clear that the low conductivity of ULE® will allow for effective cooling to 4 kelvin, which is key to eliminating thermal background for long-wave IR instrument performance. Figure 3 illustrates the thermal conductivity of candidate materials, alongside specific stiffness. ULE® may be substituted with other glasses that are better suited to cryogenic use like fused silica, which are similar in terms of processing methods, material composition and material properties. Fused silica may be an apt choice because it has a near-zero strain change when cooled from 293 kelvin to 4 kelvin.

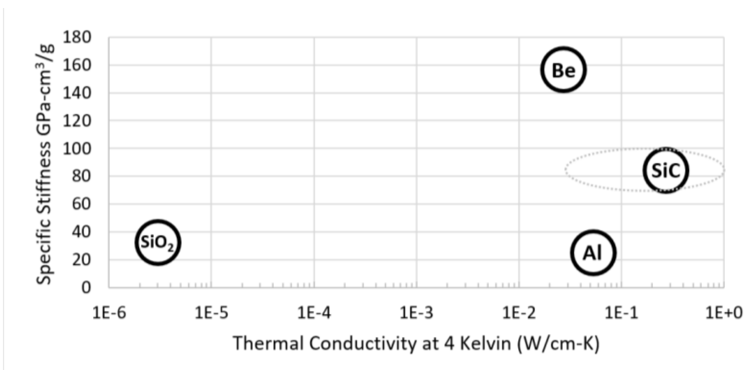

Figure 3: Specific Stiffness vs. Thermal Conductivity at 4 Kelvin for OST Candidate Materials: Fused Silica (SiO_2)[8][9], Beryllium[10][11] (Be), Silicon Carbide (SiC) [12][13] and 6061-T6 Aluminum (Al) [14][15].

Note that the properties of AlBeMet®, a metal matrix composite, are expected to be between those of aluminum and beryllium in Figure 3, depending on the grade of AlBeMet®. Also note that the dotted ellipse around SiC indicates that different grades of SiC have a wide range of properties. Specific stiffness values in Figure 3 were determined using room temperature density and stiffness; this assumes that room temperature values are representative of 4 kelvin values for these properties.

Conductivity is the dominant type of heat transfer in a 4 kelvin telescope. For a room temperature telescope, variations from 293 kelvin drive significant radiative heat transfer because of the fourth-power component of radiation. At 4 kelvin, variations from 4 kelvin drive very little radiative heat transfer, on the order of 10^8 less than at room temperature. Therefore, conductivity dominates heat transfer in a 4 kelvin telescope. It is necessary that the mirror substrates have high conductivity to enable active cooling to 4 kelvin without extending the commissioning time. It is also critical that mirror substrates have high conductivity to allow for the uniform cold, quiet thermal background necessary for IR observations.

3. CANDIDATE MATERIALS

Several materials have been identified as potential candidates. Primary considerations of material selection include performance, schedule, manufacturing capabilities, material properties and cost.

3.1 Silicon Carbide

SiC presents a low-cost alternative to beryllium. Silicon carbide can be machined and ground without any of the health hazards associated with beryllium. Silicon carbide has been demonstrated for spaceborne, cryogenic, IR operation. The largest space telescope flown as of this writing is Herschel Space Observatory, with its 3.5-meter Boostec® silicon carbide mirror built in France. OST and Herschel Space Observatory are both cryogenic, long wavelength IR telescopes. Silicon carbide mirrors larger than 2.0 m have not been demonstrated in the United States.

3.2 Aluminum

Aluminum alloys also present a low-cost alternative to beryllium. Aluminum has been demonstrated in cryogenic IR applications, but only with aperture sizes less than 1.0 m. Aluminum is the most accessible and least costly bulk material on a per-mass basis. Of all the materials, aluminum is most workable. Any machine shop capable of milling, cutting, or fastening metal parts can perform these processes on aluminum; the same cannot be said for SiC, Be, glass/ceramics, or AlBeMet®. AlBeMet® can be machined as readily as aluminum, but it is still subject to the same limitations as beryllium with respect to limiting human exposure.

3.3 Glass and Glass-Ceramics

AMSD demonstrated both beryllium and ULE® mirror segment performance at cryogenic temperatures. Beryllium had a significant advantage in terms of cryogenic wavefront error with respect to JWST requirements. However, beryllium's advantage is insignificant with respect to OST requirements, the cryogenic wavefront error measured for both the ULE® and beryllium AMSD mirrors can fit comfortably within the OST error budget. If thermal control analysis can demonstrate that ULE® can be cooled to 4 kelvin over an acceptable period of time, and be maintained constantly at a uniform 4 kelvin, there is potential to realize the significant cost and schedule advantages of ULE® substrates that was uncovered in AMSD. The cost and schedule advantages of ULE® likely apply to other glasses like fused silica, which are similar in terms of processing methods, material composition and material properties. Fused silica may be an apt choice because it has a near-zero strain change when cooled from 293 kelvin to 4 kelvin.

3.4 Beryllium

If OST, like JWST, uses beryllium mirror substrates, there are several opportunities to improve cost, schedule, and performance. A basic possibility is build-to-print reuse of the JWST segments, which would reduce design and analysis costs, increase technology readiness level (TRL), and reduce risk.

JWST mirror segments far exceed the requirements of OST, as they were designed to meet requirements for a 2 μm diffraction limited system, as opposed to a 30 um diffraction limited system. OST mirrors could still meet requirements with a 15x growth in all sources of surface figure error, including those relating to gravity, metrology, and temperature. Beryllium mirrors can be made up to 1.5 m in size using existing facilities. Polishing of beryllium is not trivial due to the formation of an oxidation layer on the mirror surface. Beryllium is not positioned as a lowest-cost, fastest-production solution, but savings could still be realized over JWST by way of:

- A lighter, less stiff, more compact mirror assembly, resulting in lighter, more compact mirror support structures
- Fewer degrees of actuation, reducing parts, complexity, and mass
- Less accurate alignment, metrology, or actuation with the same mirrors
- Removal of steps in the mirror fabrication process, like cryogenic figuring

3.5 AlBeMet®

AlBeMet® features similar processing behavior to aluminum: it is readily machined and compatible with joining techniques like fasteners, welding, and brazing. AlBeMet® can be machined as readily as aluminum, but it is still subject to the same limitations as beryllium with respect to limiting human exposure. There is little flight heritage with AlBeMet® mirror optics, but lightweight mirror substrates less than one foot in diameter[7] have been demonstrated,

5. CONCLUSION

In the wake of JWST, beryllium can be presented as a familiar, low-risk, high TRL solution, though it is not without programmatic challenges. There is potential for reuse of JWST beryllium mirror designs, analyses, and test data. AlBeMet®, an alloy of aluminum and beryllium, offers an opportunity to improve upon the machinability and interface potential of beryllium, without much degradation to thermal performance. AlBeMet® has the least relevant heritage of all materials discussed, and a substrate would weigh more than an equivalent stiffness beryllium substrate, as AlBeMet® has a lower specific stiffness.

Glass and ceramics have the advantage of a strong optic manufacturing experience, infrastructure and “polishability,” but have inherently low thermal conductivity. Low conductivity can mean many weeks spent cooling to 4 kelvin on orbit and poor temperature uniformity across mirror segments once operating equilibrium is reached. Recent developments in ceramics present possible leaps in thermal conductivity while preserving manufacturing advantages, such as the cordierite ceramic, NEXCERA™.

Herschel Space Observatory builds a great deal of confidence in SiC solutions, though scalability of a SiC monolith beyond 3.5 m is nontrivial. Highly active segmented SiC solutions are prevalent, but there is a clear path to SiC meeting OST requirements without any active figure control.

There is extensive space flight heritage for IR telescopes, up to 3.5 m in size and down to a temperature of 4 kelvin. Mirrors for IR space telescopes have successfully been made from ULE®, silicon carbide, aluminum, beryllium, and fused silica, among others. Because the OST WFE budget is roughly 15x larger than the JWST WFE budget, other test support methods, metrology methods, finishing methods and alignment methods might be employed. Because of relaxed requirements on alignment, metrology, mirror surface quality, and cryogenic WFE changes, OST offers opportunities for low areal cost and schedule, as compared to past missions.

Acknowledgements

The OST Materials Working Group helped define the driving factors and considerations for OST mirror substrate materials, under the leadership of Carly Sandin at Goddard Space Flight Center (GSFC). The OST Study Team, led by Ruth Carter at GSFC supported trade studies and discussions leading up to this work. Mike Dipirro at GSFC also supported this effort by helping define thermal performance requirements and thermal material property considerations for OST.

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